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Improved operation of a microwave pulse compressor with a laser-triggered high-pressure gas plasma switch

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The influence of laser beam parameters on the output pulses of a resonant microwave compressor with a laser-triggered plasma switch was investigated. The S-band compressor, consisting of a rectangular waveguide-based cavity and H-plane waveguide tee with a shorted side arm, was filled with pressurized dry air and pumped by 1.8-μs-long microwave pulses of up to 450 kW power. A Nd:YAG laser was used to ignite the gas discharge in the tee side arm for output pulse extraction. The laser beam (at 213 nm or 532 nm) was directed along the RF electric field lines. It was found that the compressor operated most effectively when the laser beam was focused at the center of the switch waveguide cross-section. In this case, the power extraction efficiency reached ~47% at an output power of ~14 MW, while when the laser beam was not focused the maximal extraction efficiency was only ~20% at ~6 MW output power. Focusing the laser beam resulted also in a dramatic decrease (down to <1 ns) in the delay of the output pulses' appearance with respect to the time of the beam's entrance into the switch, and the jitter of the output pulses' appearance was minimized. In addition, the quality of the output pulses' waveform was significantly improved. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4960981]

Microwave pulse compressors remain of interest for decades as sources of high-peak power (hundreds of megawatts) of nanosecond-scale duration.[1] The attractiveness of time-domain compression for the generation of such pulses is related to employing commercial primary sources of megawatt power level. This implies that the gain of the compressor is high (~20 dB) and that it is necessary to use a high-pressure gas discharge for switching. In such compressors, the resonant cavity is charged by a primary source while the cavity coupling to a load remains negligibly weak; then the plasma discharge is initiated in the switch, the cavity becomes strongly coupled to a load, and the stored microwave energy is rapidly extracted from the cavity. Thus, the efficiency and reproducibility of the switch operation are key issues for the compressor, since the discharge development at a high pressure is a process of a probabilistic nature accompanied by significant RF energy losses for electron collisions.

The use of a powerful short-pulse (a few nanoseconds) laser beam for ignition of the microwave discharge in the compressor switch[2,3] significantly improves reproducibility and allows the synchronization of several compressors.[4,5] Meanwhile, the efficiency of the power extraction from the compressor cavity remains rather low; values of 30%–40% were reported in an early paper,[2] and the same level was obtained in recent studies.[6,7] The efficiency of the power extraction is defined as the ratio of the peak output power to the available power at a given stored energy, i.e., the power of the traveling waves forming the standing wave in the cavity. Below we shall refer to this as the *stored* power.

The laser beam generates seed electrons for the discharge development, which is then determined, at a given pressure and gas type, by the RF electric field in the switch. The discharge originates from the center of the waveguide cross-section, and the plasma in the switch appears as a filament expanding along the RF electric field.[6] This process was simulated numerically,[8] and it was shown that a low extraction efficiency is inevitable when the time of the filament formation with sufficiently high plasma density is longer than the round-trip time of the traveling wave along the cavity (output pulse length). In this case, the extraction of the output pulse limits its own power, since the RF electric field in the switch decreases to the level at which it no longer supports the electron avalanche. The simulations described in Ref. 8 showed that such a scenario can be avoided (an extraction efficiency of ~75% was obtained) when seed electrons with sufficient density are set in a filament-like volume parallel to the RF electric field. In practice, such electron seeding can be achieved by using a laser beam directed along the RF electric field in the switch waveguide and focused with a long-focus lens to enhance its intensity in an extended region across the waveguide. This motivated the present research, in which the S-band compressor operation was compared when the high-pressure discharge in the switch was triggered by focused and unfocused laser beams of either 213 nm or 532 nm wavelength and variable intensity.

The experimental setup is shown schematically in Fig. 1. The compressor assembly comprised WR284 waveguide-based components: the 40-dB directional coupler with the iris served as the cavity (so that the stored power was measured directly) and the H-plane tee with the side arm shorted by an adjustable membrane was used as the interference switch. The system was filled with dry air at ≈2.6×10^5 Pa absolute pressure. The cavity was charged by 1.8-μs-long input pulses produced by a frequency-tunable CPI VMS1177 magnetron; the operating frequency was 2765.8 MHz, and the input power

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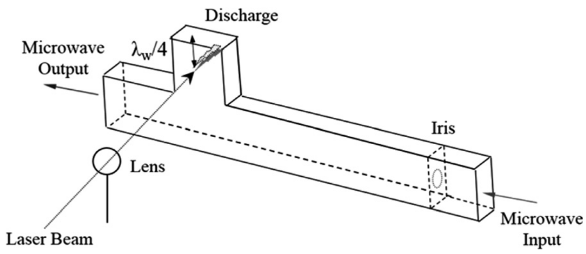

FIG. 1. Schematic of experimental setup.

ranged from 300 to 450 kW. An EXPLA Nd:YAG laser was employed for the discharge ignition; the laser beam, at a wavelength of either 213 or 532 nm, ~5 ns FWHM, entered the tee side arm at the quarter guide wavelength from the membrane through a slot (2 mm × 7 mm) made along the centerline of the waveguide wide wall. Using a UV fused silica lens (340 mm or 419 mm focal length for the 213 and 532 nm wavelength, respectively), the laser beam was focused either at the center of the waveguide cross-section or at the back wide wall of the waveguide. The energy of the laser beam pulse was up to 5 mJ and up to 50 mJ for the 213 nm and 532 nm wavelength, respectively.

The microwave signals (input, output, reflected, and from inside the cavity) were recorded as RF voltage from the directional couplers by an Agilent Infinium 54855A 6 GHz oscilloscope. To determine the delay of the output pulse appearance with respect to the laser beam's entrance into the tee side arm, a partial reflection from the UV fused silica sealing window was registered by a photodiode.

The most effective operation of the compressor was found to be achieved when the laser beam was focused at the center of the side arm waveguide cross-section. In Fig. 2, the microwave output pulses obtained at the same stored power in the cavity with focused and unfocused UV laser beams of the same intensity are presented. One can see that, for the focused beam, the peak power is more than two times higher, the rise time of the pulse is about two times shorter, the "flattop" is longer, and the delay with respect to the triggering event is dramatically shorter than for the unfocused beam. There is a good qualitative agreement between the output pulse waveforms and delays and the results of the simulations,[8] in which the seed electrons set in the filament-like volume differed in density by six orders of magnitude. Thus, the focused beam evidently creates a much higher density of seed electrons, so that plasma filaments having sufficient length and density for efficient microwave reflection are formed in a time much shorter than the output pulse duration.

In Fig. 3, the power extraction efficiency and appearance delay are shown for a number of pulses with UV beams of different intensities focused at the center and at the back wall of the switch waveguide. A comparison of these cases is of interest since, on the one hand, focusing the 213-nm laser beam at the wall results in intense photoelectron emission and plasma formation,[9] while on the other hand, the region of enhanced laser beam intensity inside the waveguide for back-wall focusing is shorter than for center focusing. It is seen in Fig. 3(a) that the extraction efficiency in the case of center focusing reached ≈47% (at the output power of 13–14 MW), whereas in the case of back-wall focusing, it was ~35%. It is also seen that there is no noticeable influence of the laser beam intensity on the extraction efficiency (and hence on the output power). Meanwhile, increasing intensity shortens the delay in the output pulse's appearance (Fig. 3(b)) and reduces its jitter. It should be noted that, in spite of lower peak power, output pulses appeared more quickly with back-wall focusing; one can see in Fig. 3(b) that the delay is decreased in this case to less than 1 ns. This can be explained by an increased density of seed photoelectrons at that location. Let us note also that traces of melting were observed with back-wall focusing, but not with center focusing. The jitter, however, was about the same with back-wall and center focusing.

Experiments with the 532-nm laser beam yielded results similar to those obtained with the 213-nm laser beam. The maximal efficiency of power extraction was also ~47% (the maximal output power was ≥12 MW), as shown in Fig. 4. The intensity of the laser beam was, however, an order of magnitude higher than in the UV case; this can be explained by the significantly lower energy of the photons. Another difference of the compressor switching with the 532-nm laser

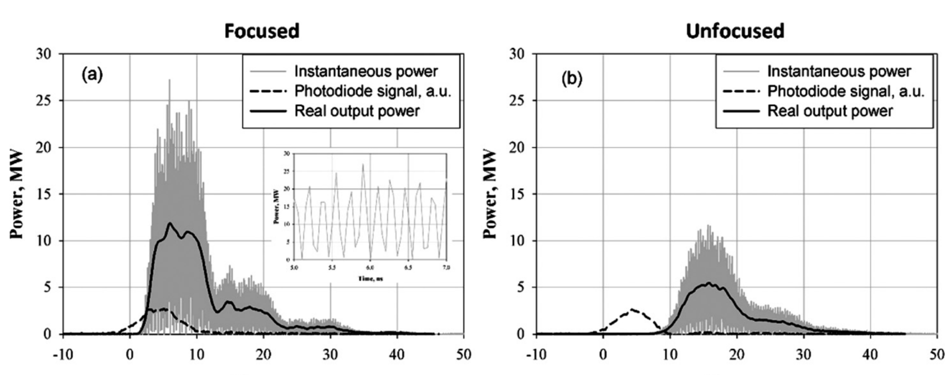

FIG. 2. Instantaneous (gray) and real (black) power of the compressor output pulses, calculated from recorded RF voltage, obtained with the 213-nm wavelength beam of ~1 mJ pulse energy focused at the center of the side arm waveguide cross-section (a) or unfocused (b). The stored power was ≈29 MW for both cases. The dashed curves show the signal from the photodiode (a.u.); zero time corresponds to the moment when the laser beam enters the waveguide. The inset in the graph (a) shows the fine details in the instantaneous power corresponding to the time interval from 5 to 7 ns around the peak (interval between the scope's samples is 50 ps).

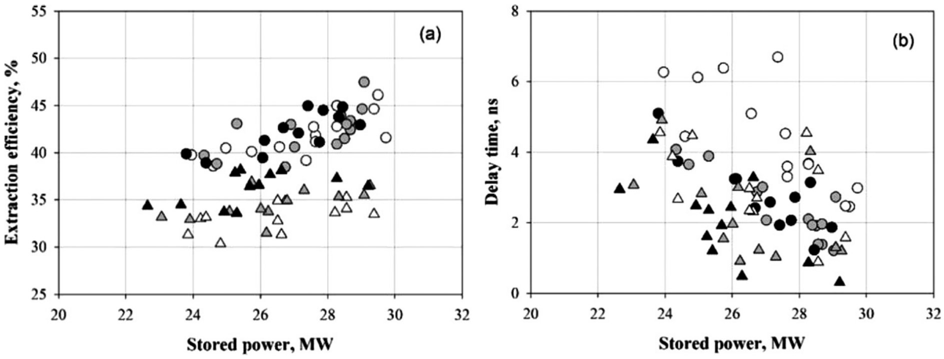

FIG. 3. Efficiency of the power extraction (a) and delay of the output pulse's appearance (b) vs. power stored in the cavity for triggering by the 213-nm wavelength beam focused at the center of the waveguide cross-section (circles) and at the back wall (triangles). The beam pulse energy is 1 mJ (white), 3.5 mJ (grey), and 5 mJ (black).

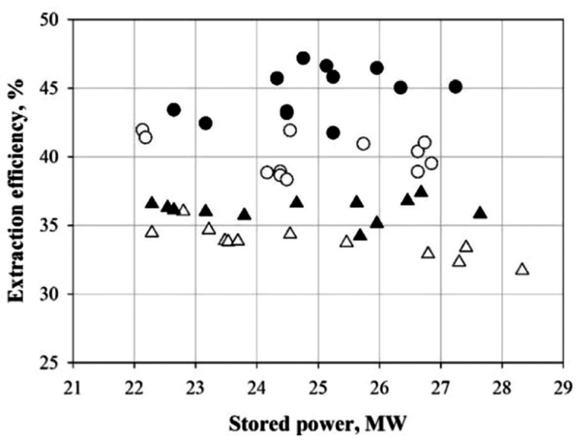

FIG. 4. Efficiency of the power extraction vs. power stored in the cavity for triggering by the 532-nm wavelength beam focused at the center of the waveguide cross-section (circles) and at the back wall (triangles). The beam pulse energy is 31 mJ (white) and 43 mJ (black).

beam is a slight influence of the laser intensity on the output power, as shown in Fig. 4. The output pulse waveforms observed with the focused and unfocused beam were the same as for the UV case (see Fig. 2). The extraction efficiency with the unfocused beam, regardless of whether UV or visible light was used, did not exceed 20% at 5–6 MW output power.

In summary, when the laser beam was focused with a long-focus lens, providing an increased amount of seed electrons in an extended region along the RF electric field in a pressurized gas-filled switch of a resonant microwave compressor, its operation was definitely improved: the power of the output pulses increased by a factor of two and more, the waveform became close to rectangular, and the jitter of appearance decreased to values close to the period of RF oscillations. A maximal power extraction efficiency of $\sim$47% was observed when the laser beam was focused at the center of the switch waveguide cross-section, with both the 213-nm and 532-nm laser beams. A minimal delay ($<$1 ns) in the output pulses' appearance with respect to the moment at which the laser beam entered into the switch was obtained by focusing the laser beam at the wall of the switch waveguide; the extraction efficiency in this case was lower, $\sim$35%, probably because the major part of the seed electrons was produced in the vicinity of the wall, so that the formed plasma filament was shorter. The microwave output power was not affected by the laser beam intensity, except in the case of the focused 532-nm wavelength beam, where increasing intensity leads to a slight power increase. An increase in the intensity beyond the level accessible in the present experiments is of interest, as it may provide the increase in power extraction efficiency up to $\sim$75% that is shown in numerical simulations.[8]

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